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CLINICAL TRIALS AND OBSERVATIONS

A prospective study on drug monitoring of PEGasparaginase and *Erwinia* asparaginase and asparaginase antibodies in pediatric acute lymphoblastic leukemia

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Key Points

- Use of native *E coli* asparaginase in induction leads to high hypersensitivity rates to PEGasparaginase in intensification.
- Switching to *Erwinia* asparaginase leads to effective asparaginase activity levels in most patients who experienced an allergy to PEGasparaginase.

This study prospectively analyzed the efficacy of very prolonged courses of pegylated *Escherichia coli* asparaginase (PEGasparaginase) and *Erwinia* asparaginase in pediatric acute lymphoblastic leukemia (ALL) patients. Patients received 15 PEGasparaginase infusions (2500 IU/m^2 every 2 weeks) in intensification after receiving native *E coli* asparaginase in induction. In case of allergy to or silent inactivation of PEG-asparaginase, *Erwinia* asparaginase (20 000 IU/m^2 2-3 times weekly) was given. Eighty-nine patients were enrolled in the PEGasparaginase study. Twenty (22%) of the PEGasparaginase–treated patients developed an allergy; 7 (8%) showed silent inactivation. The PEGasparaginase level was 0 in all allergic patients (grade 1-4). Patients without hypersensitivity to PEGasparaginase had serum mean trough levels of 899 U/L. Fifty-nine patients were included in the *Erwinia* asparaginase study; 2 (3%) developed an allergy and none silent inactivation. Ninety-six percent had at least 1 trough level ≥100 U/L. The serum asparagine level was not always completely depleted with *Erwinia* asparaginase in contrast to PEGasparaginase. The presence of asparaginase antibodies was related to allergies and silent inactivation, but with low specificity (64%). Use of native *E coli* asparaginase in induction leads to high hypersensitivity rates to PEGasparaginase in intensification. Therefore, PEGasparaginase should be used upfront in induction, and we suggest that the dose could be lowered. Switching to *Erwinia* asparaginase leads to effective asparaginase levels in most patients. Therapeutic drug monitoring has been added to our ALL-11 protocol to individualize asparaginase therapy. (*Blood*. 2014;123(13):2026-2033)

Introduction

Asparaginase is an enzymatic drug and an essential component of the combination chemotherapy of childhood acute lymphoblastic leukemia (ALL).[1] This drug depletes asparagine in the blood, and the malignant lymphoid cells that depend on extracellular asparagine will thus go into apoptosis.[2,3] Currently, several asparaginase agents are available on the market. Either these are derived from *Escherichia coli* in its native form (native *E coli* asparaginase) or as a pegylated enzyme (PEGasparaginase). Otherwise, asparaginase is extracted from *Erwinia chrysanthemi* (*Erwinia* asparaginase).

It has been shown that intensified use of asparaginase increases event-free survival (EFS) for children with ALL by 10% to 15%.[4-7] Administration of asparaginase can be limited by the occurrence of hypersensitivity reactions to asparaginase, like allergic or anaphylactic reactions.[8] Patients with these reactions are switched to another asparaginase product to ensure that they are exposed to asparaginase according to the treatment plan and to ensure an optimal EFS.[9] Clinical allergy is associated with inactivation of asparaginase by antibodies.[10,11] Formation of asparaginase antibodies (AAAs) can also neutralize

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asparaginase without any clinical signs of hypersensitivity, so-called silent inactivation. Panosyan et al and Vrooman et al showed that children with silent inactivation of native *E coli* asparaginase had a poorer outcome because they were not switched to alternative asparaginase agents, whereas those with clinically overt allergy were switched and had no poorer outcome.[8,12] In most protocols, asparaginase is given during the induction course, followed by asparaginase-free consolidation courses, and after that asparaginase is again given during the intensification/reinduction course. The majority of hypersensitivity reactions occur during the intensification phase.

The Dutch Childhood Oncology Group (DCOG) ALL-10 protocol used native *E coli* asparaginase in induction and the less immunogenic PEGasparaginase in the intensification phase in an attempt to prevent hypersensitivity reactions.[13] In case of either hypersensitivity to PEGasparaginase or silent inactivation, children were switched to *Erwinia* asparaginase as a second-line agent in intensification. Only a few studies have been performed on silent inactivation using intensive PEGasparaginase[14] or intensive *Erwinia* asparaginase.[15,16]

The aim of this prospective drug-monitoring study was to analyze the efficacy of very prolonged use of PEGasparaginase and *Erwinia* asparaginase by assessing asparaginase activity, asparagine, glutamine levels, and AAAs.

Methods

Patients

Children between 1 and 18 years of age with newly diagnosed ALL and stratified as medium-risk patients were included in the prospective PEGasparaginase study from May 2009 until October 2012 in 2 pediatric oncology centers. Patients were assigned to the medium-risk group based on a prednisone good response at day 8, cytomorphologic complete remission at day 33, and minimal residual disease positivity at day 33 and/or day 79 (before the start of protocol M), but minimal residual disease level at day 79 $<10^{-3}$ and no presence of the t(4;11)(q11;q23) translocation or the corresponding fusion gene MLL/AF4 in the leukemia cells at diagnosis. Children who had an allergy to PEGasparaginase or silent inactivation were switched to *Erwinia* asparaginase and included in the prospective *Erwinia* asparaginase study. Because of the expected low number of allergic reactions to PEGasparaginase, the latter study was carried out in all 7 pediatric oncology centers in the same study period.

The Institutional Review Board approved this study before patient enrollment. Informed consent was obtained from parents or guardians and from patients ≥12 years of age. This study was in accordance with the Declaration of Helsinki.

DCOG ALL-10 treatment protocol

Patients were stratified into 3 risk groups after induction treatment: standard risk, medium risk, and high risk.[17] The treatment scheme of the ALL-10 protocol and the intensification phase of the medium-risk patients in greater detail are given in supplemental Figure 1 (available on the *Blood* Web site).

All patients received 8 doses of native *E coli* asparaginase (5000 IU/m^2 per dose) every 3 days in induction. If a patient was stratified as medium risk, PEGasparaginase as a first-line agent (2500 IU/m^2 per dose every other week) was given for a total of 15 doses during the first 30 weeks of intensification. In case of an allergy to or silent inactivation of PEGasparaginase, the drug was replaced by *Erwinia* asparaginase as a second-line agent (20 000 IU/m^2 per dose) 3 times per week to complete 30 weeks of asparaginase therapy. All asparaginase agents were administered intravenously.

Study design

In the PEGasparaginase study, the PEGasparaginase activity trough levels and AAAs were measured in serum at the start of intensification (week 0); in weeks 2, 4, 6, 8, 10, 14, 16, 24, 26, and 28; and also 1 week after administration in weeks 3, 9, 15, and 25. Serum asparagine, aspartic acid, glutamine, and glutamic acid levels were measured at weeks 0, 2, 4, 14, and 24 during PEGasparaginase therapy.

Children who had an allergy to PEGasparaginase or silent inactivation were included in the *Erwinia* asparaginase study. For this study, 6 blood samples of *Erwinia* asparaginase activity levels during the first 2 weeks of therapy were obtained from children who received *Erwinia* asparaginase (Monday, Wednesday, and Friday). In case of high activity levels (72-hour levels ≥100 U/L), the frequency of administration of *Erwinia* asparaginase was reduced to 2 times per week. Thereafter, every 4 weeks a blood sample was assessed.

Allergy was graded according to the National Cancer Institute Common Terminology Criteria for Adverse Events version 3.0. Silent inactivation was defined as serum PEGasparaginase activity level <100 U/L at day 7 ± 1 or <20 U/L at day 14 ± 1 after administration in a patient without clinical symptoms of allergy. Silent inactivation of *Erwinia* asparaginase was defined as serum asparaginase activity level <20 U/L at day 2 after administration of *Erwinia* asparaginase in patients without clinical allergy.

Laboratory measurements

Serum asparaginase activity and amino acid levels were processed and assessed as described earlier.[18,19] Antibodies against native *E coli* asparaginase (Asparaginase medac) (Coli-AAAs), against PEGasparaginase (Oncaspar) (PEG-AAAs), and against *Erwinia* asparaginase (Erwinase) (*Erwinia*-AAAs) were measured by enzyme-linked immunosorbent assays (see supplemental Methods). All AAAs were expressed as optical density (OD) readings. Samples were defined as positive for AAAs if the Coli-AAA OD was >0.13, if the PEG-AAA OD was >0.25, and if the *Erwinia*-AAA OD was >1.96 standard deviations above the negative control processed mean (using Westgard rules).[20]

To evaluate if Coli-AAAs in induction predict an allergy or silent inactivation in intensification, we measured Coli-AAAs after induction in a single center (Rotterdam).[21]

Statistical analysis

The data were analyzed with the software package SPSS, version 20.0.0.1 (SPSS, Chicago, IL). Repeated measurements of the asparaginase activity levels were evaluated using mixed models analysis of variance (see supplemental Methods). The antibody levels were compared using nonparametric tests. The role of Coli-AAAs at day 79 (at the start of consolidation; protocol M) was analyzed to predict an allergy or silent inactivation at day 140 (start of intensification); for this, sensitivity and specificity were given. Sensitivity and specificity were calculated with the Fisher's exact test for 2-by-2 contingency tables.

The occurrence of allergy to or silent inactivation of PEGasparaginase related to age and gender was investigated with the χ^2 test/ Fisher's exact tests where appropriate. A 2-sided P value $< .05$ was considered statistically significant. Data are presented as mean ± standard error of the mean (SEM) or specified otherwise.

Results

PEGasparaginase study

Supplemental Table 1 displays the characteristics of 89 patients included in the PEGasparaginase study. Twenty of the 89 (22%) patients had clinical allergic reactions to PEGasparaginase (6 grade 1, 7 grade 2, and 7 grade 3), and 7 of 89 (8%) patients showed silent inactivation. Eighteen of the 20 (90%) allergic reactions occurred on the second PEGasparaginase dose. Age, gender, and ALL immunophenotype did not differ between patients with or without allergy/ silent inactivation of PEGasparaginase.

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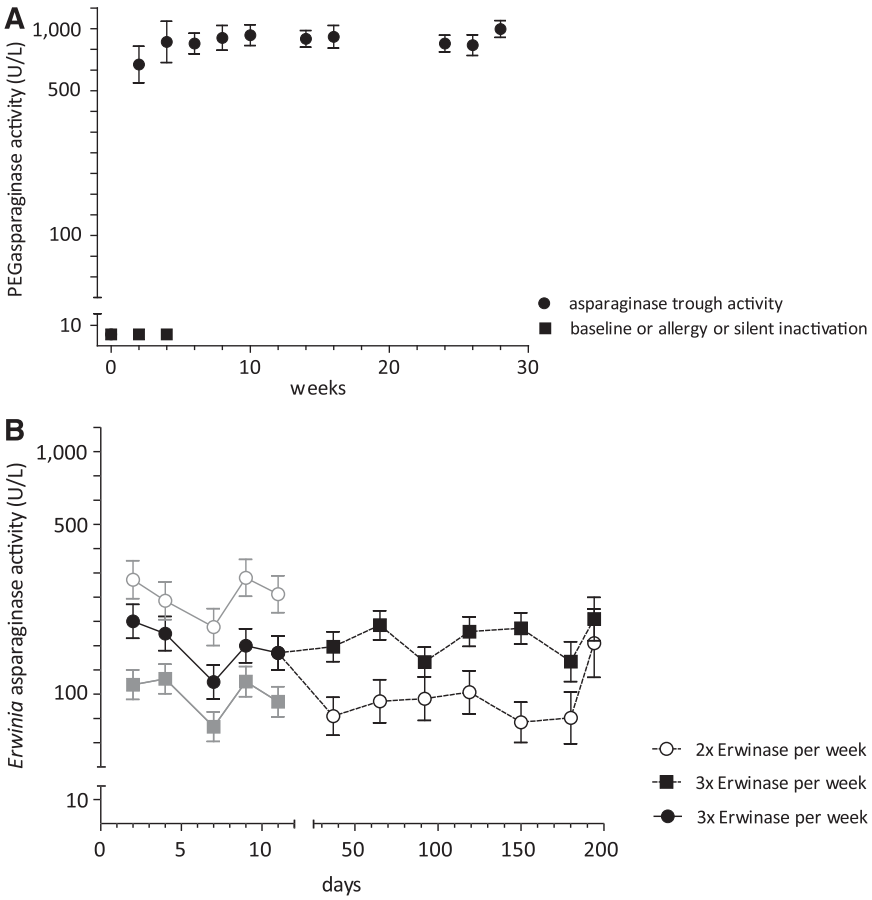

Figure 1. Pharmacokinetics of very prolonged PEGasparaginase and *Erwinia* asparaginase use. (A) Serum PEGasparaginase activity levels (mean ± SEM) of children with or without allergy to or silent inactivation of PEGasparaginase (2500 IU/m^2 every other week) (n = 62). (B) Serum *Erwinia* asparaginase activity levels (mean ± SEM) of children without allergy to *Erwinia* asparaginase (20 000 IU/m^2 2-3 times per week) (n = 57). In panel B, 3 curves are shown in the first 2 weeks of *Erwinia* asparaginase therapy. The upper curve (white open circles) shows 19 children who had high *Erwinia* asparaginase levels (72-hour levels ≥100 U/L) and were switched to infusions 2 times per week after the first 2 weeks of *Erwinia* asparaginase therapy. The lower curve (gray blocks) shows 38 children who had low *Erwinia* asparaginase levels (72-hour levels <100 U/L) and continued infusions 3 times per week after the first 2 weeks of *Erwinia* asparaginase therapy. The middle curve (closed circles) shows analysis of variance estimates of all 57 children receiving *Erwinia* asparaginase 3 times per week in the first 2 weeks.

Serum PEGasparaginase activity levels were measured in 592 samples of 89 children (Figure 1A). PEGasparaginase activity levels were not related to age (<10 years or ≥10 years) or gender (both $P = .2$). Patients without allergy to and without silent inactivation of PEGasparaginase had a mean trough activity level of 899 U/L (see also supplemental Figure 2). All 20/89 (22%) allergic patients (including grade 1-4 Common Terminology Criteria for Adverse Events) showed PEGasparaginase activity levels of 0. This was not attributable to the fact that the infusion was stopped because 18 patients showed their allergic reactions at the second dose; the serum asparaginase activity level after the first full dose already appeared to be 0 in all 18 cases. Moreover, in 4 cases the second full PEG-asparaginase dose was given with clemastine and hydrocortisone, also resulting in unmeasurable serum activity levels of PEGasparaginase after the second dose. All allergic patients were switched to *Erwinia* asparaginase. Two of the 7 children with silent inactivation were switched to *Erwinia* asparaginase. The other 5 patients continued with PEGasparaginase because real-time asparaginase measurements were not available at that moment. Those were excluded from further analysis.

At the start of the intensification phase, the asparagine levels were normal in almost all patients (normal range 40-80 μM). All children without an allergy to PEGasparaginase and without silent inactivation had complete asparagine depletion over time with a lower level of quantification (LLQ) of 0.2 μM (Figure 2A). Children with an allergy to PEGasparaginase or silent inactivation showed no asparagine depletion (Figure 2A). Supplemental Figure 3A shows PEGasparaginase activity levels in relation to the asparagine levels. Figure 2B-D displays aspartic acid, glutamine, and glutamic acid levels. Aspartic acid levels increased after 1 PEGasparaginase infusion in children without allergy and without silent inactivation in line with the asparagine depletion. Thereafter, no changes were seen. No glutamine depletion was seen during PEGasparaginase therapy. Glutamic acid levels increased after the first 2 PEGasparaginase infusions in children without allergy and without silent inactivation; no changes were seen thereafter.

Predictive value of Coli-AAAs in induction for an allergy or silent inactivation in intensification

Coli-AAAs were measured serially in 40 patients; 11/40 (27.5%) had allergy and 4/40 (10%) had silent inactivation, respectively, in intensification. The sensitivity of Coli-AAAs at day 79 to detect allergy or silent inactivation in intensification (day 140) was 87% (95% CI, 60% to 98%), and specificity was 64% (95% CI, 43% to 82%).

At day 79, the Coli-AAA levels of children with allergy to or silent inactivation of PEGasparaginase in the subsequent intensification phase were significantly higher than those in children without ($P = .02$). The same was found at day 140 ($P = .006$) (Figure 3A-B). All children allergic to PEGasparaginase, except 1, had Coli-AAAs at the start of intensification (day 140) (Figure 3B).

Only 1 patient had PEG-AAAs at day 140 (Figure 3C). The levels of Coli-AAAs and PEG-AAAs increased significantly from day 140 to day 154 after the first PEGasparaginase infusion in allergic patients ($P = .002$ and $P < .001$, respectively). All allergic children except 1 developed PEG-AAAs after the first PEGasparaginase infusion. All children with silent inactivation had Coli-AAAs before (day 140) and after (day 154) the first PEGasparaginase

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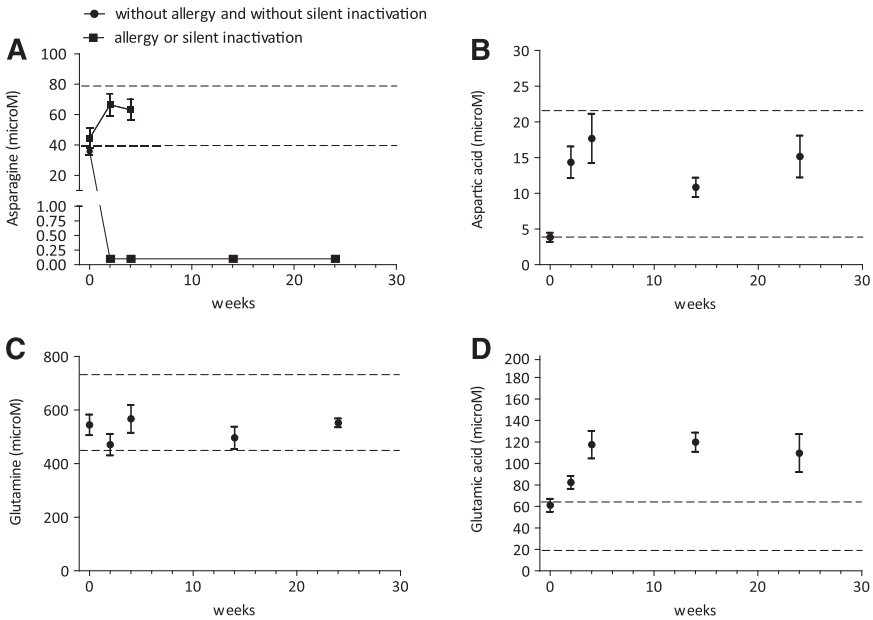

Figure 2. Pharmacodynamics of very intensified PEGasparaginase courses. Serum asparagine (A), aspartic acid (B), glutamine (C), and glutamic acid (D) levels (mean ± SEM) during PEGasparaginase therapy (2500 IU/m^2) in children without allergy to PEGasparaginase and without silent inactivation. Dashed lines show normal values of asparagine (40-80 μM), aspartic acid (4-22 μM), glutamine (457-738 μM), and glutamic acid (18-65 μM). The LLQ of asparagine is 0.2 μM.

infusion. Only 2/7 silent inactivation patients had PEG-AAAs after the first PEGasparaginase infusion (day 154), and patients with silent inactivation had lower PEG-AAAs at day 154 than patients with clinical allergy ($P = .001$).

Erwinia asparaginase study

Supplemental Table 1 presents the characteristics of the 59 patients with an allergy to or silent inactivation of PEGasparaginase in this 7-center study; 25 patients had already participated in the PEGasparaginase study.

Two of the 59 (3%) patients developed an allergy to *Erwinia* asparaginase; one showed a grade 3 allergy at the fourth infusion, and the other a grade 2 allergy at the sixth infusion. These 2 patients did not receive further asparaginase therapy. No patients with silent inactivation of *Erwinia* asparaginase were seen.

Serum *Erwinia* asparaginase activity levels were measured in 444 samples of 57 patients without allergy to *Erwinia* asparaginase to complete 30 weeks of exposure (Figure 1B). The 2 children with an allergy to *Erwinia* asparaginase had asparaginase activity levels of 0. This was not attributable to the fact that the infusion was stopped, because the asparaginase level of the previous dose already appeared to be 0 in both patients. Also, in both cases, the next full *Erwinia* asparaginase dose was given with clemastine and hydrocortisone, resulting in unmeasurable serum *Erwinia* asparaginase activity levels.

Table 1 shows the *Erwinia* asparaginase activity levels during intensification therapy. *Erwinia* asparaginase activity levels were not related to age (<10 years or ≥10 years) or gender ($P = .7$ and $P = .4$, respectively). In the first 2 weeks, all children received 6 doses of *Erwinia* asparaginase. Of the nonallergic *Erwinia*-asparaginase patients in the first 2 weeks, 55/57 (96%) had at least 1 *Erwinia* asparaginase activity level ≥100 U/L and 57/57 (100%) had ≥50 U/L. In 65% and 85% of all patients, all *Erwinia* asparaginase activity levels in the first 2 weeks were ≥100 U/L and ≥50 U/L, respectively. Median trough levels were 183 U/L at 48 hours and 93 U/L at 72 hours. Nineteen children (33%) were switched to

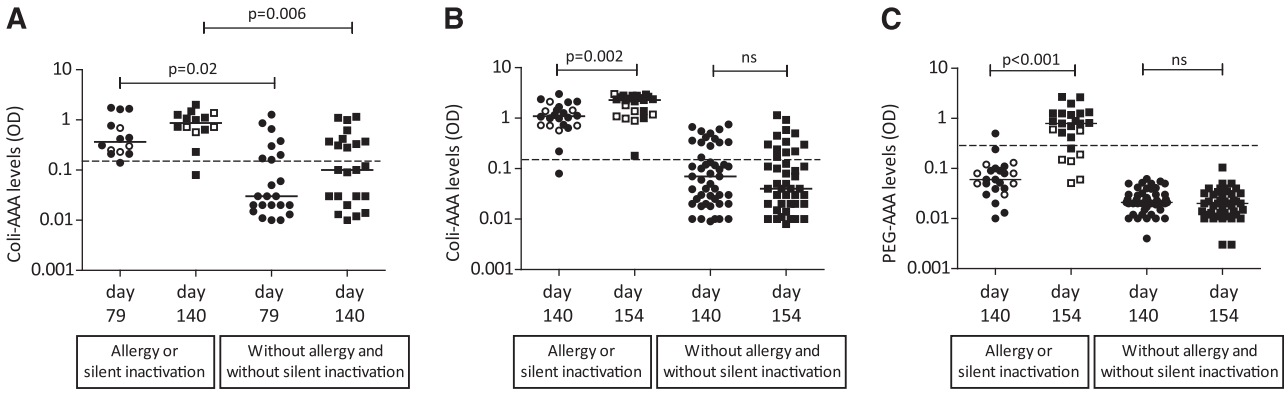

Figure 3. Patients with AAAs during the consolidation phase and in the first two weeks of the intensification. Serum AAAs against native *E coli* asparaginase (Coli-AAA levels) of patients at day 79 (start of the consolidation phase) and at day 140 (start of the intensification) (A), and Coli-AAA levels and serum AAAs against PEGasparaginase (PEG-AAA levels) at day 140 (before first PEGasparaginase dose) and at day 154 (14 days after first PEGasparaginase dose) (B-C). Dashed lines indicate that samples were defined as positive for AAAs if the Coli-AAA OD was >0.13 and if the PEG-AAA OD was >0.25. Closed circles and blocks show cases with allergy or cases without allergy and without silent inactivation; silent inactivation cases are shown by open circles and blocks. Median Coli-AAA and PEG-AAA levels are indicated by bars. NS, not significant.

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Table 1. Serum *Erwinia* asparaginase trough levels ≥20 U/L, ≥50 U/L, or ≥100 U/L

	Erwinase activity median (range)	Samples*			Patients (n = 57)		
		≥20	≥50	≥100	≥20	≥50	≥100
First 2 weeks of *Erwinia* asparaginase therapy							
3 times per week	157 (11-913)	98%	85%	65%	95%†	60%†	32%†
At least 1 sample above 20, 50, or 100 U/L					100%	100%	96%
Week 6 to week 30 of *Erwinia* asparaginase therapy							
3 times per week, 48-h interval	182 (22-737)	100%	94%	77%	100%†	87%†	47%†
At least 1 sample above 20, 50, or 100 U/L					100%	100%	100%
2 times per week, 72-h interval	83 (14-908)	96%	86%	34%	95%†	68%†	11%†
At least 1 sample above 20, 50, or 100 U/L					100%	100%	68%

The table is based on 57 patients without allergy to *Erwinia* asparaginase. The 2 patients with clinical allergy to *Erwinia* asparaginase were removed from this group. The table shows the data of the period week 6 to week 30 of *Erwinia* asparaginase therapy of 142 samples of 38 patients who continued infusions 3 times per week after the first 2 weeks of *Erwinia* asparaginase therapy and the data of 71 samples of 19 patients who were switched to infusions 2 times per week after the first 2 weeks of therapy. h, hour.

*For first 2 weeks of *Erwinia* asparaginase therapy, n = 231 samples; for week 6 to week 30 of *Erwinia* asparaginase therapy, n = 213 samples.

†Number of patients with all samples above 20 U/L, 50 U/L, or 100 U/L.

twice-weekly infusions because high activity levels (72-hour levels ≥100 U/L) were measured in the first 2 weeks.

Children receiving therapy 2 times per week showed a significant decrease of *Erwinia* asparaginase activity levels at day 37 (week 6) as compared with day 11 (week 2) (P = .002), whereas children continuing *Erwinia* asparaginase 3 times per week showed a significant increase of activity levels (P = .004) (Figure 1B). The *Erwinia* asparaginase activity levels remained stable thereafter for all patients. Concerning the nonallergic patients during *Erwinia*-asparaginase therapy, 57/57 (100%) had at least 1 *Erwinia* asparaginase activity level ≥100 U/L after the first 2 weeks. Median trough levels were 177 U/L at 48 hours and 86 U/L at 72 hours.

Before the start of *Erwinia* asparaginase, the asparagine levels were normal (normal range 40-80 μM). During repeated asparagine measurements, these levels were strongly depleted but not always fully depleted over time with an LLQ of 0.2 μM (Figure 4A). The 2 children with an allergy to *Erwinia* asparaginase showed no asparagine depletion.

Supplemental Figure 3B shows *Erwinia* asparaginase activity levels in relation to the asparagine levels, and Figure 4B-D displays aspartic acid, glutamine, and glutamic acid levels. No glutamine depletion was seen during therapy; however, after 6 weeks of *Erwinia* asparaginase therapy, the glutamine levels were decreased, but not significantly.

Figure 5 presents the *Erwinia*-AAA and *Erwinia* asparaginase activity levels over time. In total, 38% of patients developed *Erwinia*-AAAs during therapy, all at days 37, 65, and 92. Thereafter, the levels dropped again to baseline values. The presence of *Erwinia*-AAAs did not influence *Erwinia* asparaginase activity levels. No silent inactivation was seen during therapy. Both children (3%) with an allergy to *Erwinia* asparaginase had detectable *Erwinia*-AAAs.

Discussion

This prospective drug monitoring of asparaginases has resulted in several important findings. First, if patients show no clinical allergy to or silent inactivation of PEGasparaginase, the serum levels are too high using a schedule of 2500 IU/m^2 every other week. Based on this finding, we suggest that the administered PEGasparaginase dose can be lowered. This dose reduction seems feasible because different

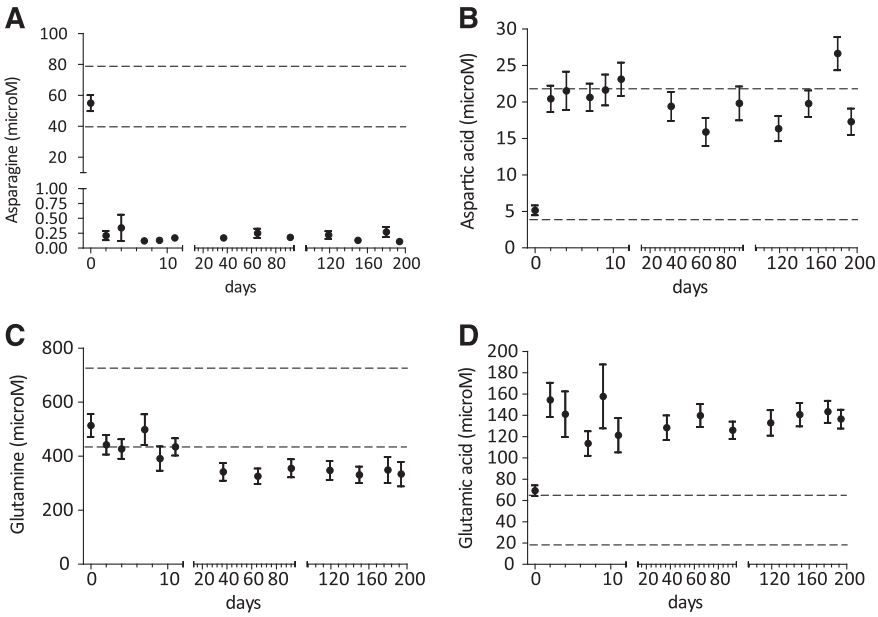

Figure 4. Pharmacodynamics of very intensified *Erwinia* asparaginase courses. Serum asparagine (A), aspartic acid (B), glutamine (C), and glutamic acid (D) levels (mean ± SEM) during *Erwinia* asparaginase therapy (20 000 IU/m^2) in children without allergy to *Erwinia* asparaginase and without silent inactivation. Dashed lines show normal values of asparagine (40-80 μM), aspartic acid (4-22 μM), glutamine (457-738 μM), and glutamic acid (18-65 μM). The LLQ of asparagine is 0.2 μM.

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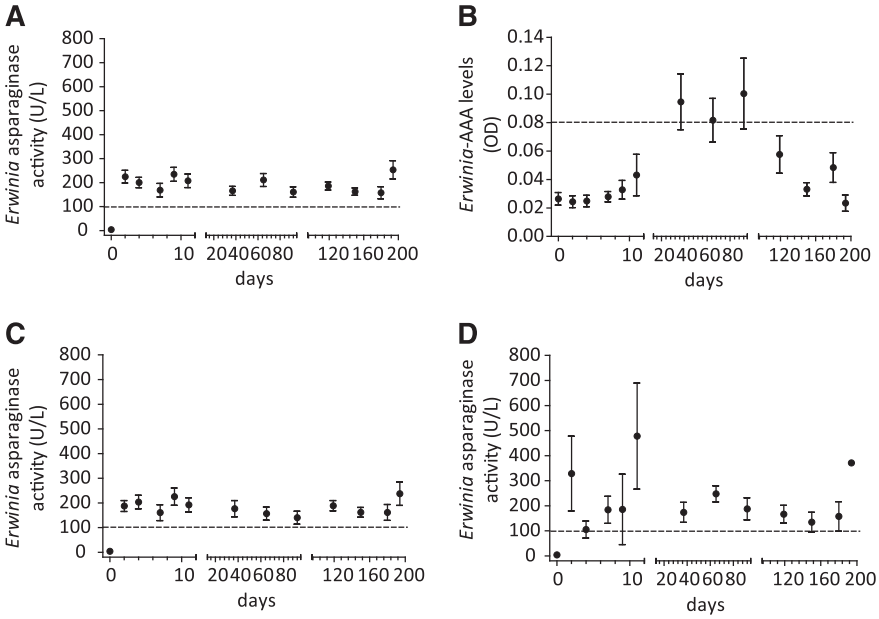

Figure 5. Pharmacokinetics of very prolonged *Erwinia* asparaginase use in relation to AAAs. Serum *Erwinia* asparaginase activity (A) and serum AAAs (B) against *Erwinia* asparaginase (*Erwinia*-AAAs) over time. Serum *Erwinia* asparaginase activity levels of patients without *Erwinia*-AAAs (C) and with *Erwinia*-AAAs (D) (mean ± SEM). Dashed lines in panels A, C, and D indicate *Erwinia* asparaginase activity level of 100 U/L. The dashed line in panel B indicates samples defined as positive for *Erwinia*-AAAs if the OD was >1.96 standard deviations above the negative control processed mean (using Westgard rules).[20]

reinduction protocols used 1000 IU/m^2 PEGasparaginase with adequate trough levels of ≥100 U/L in ~80% of the patients.[22,23] Appel et al showed earlier that 1000 IU/m^2 PEGasparaginase in induction resulted in asparaginase levels above 100 U/L for at least 2 weeks with complete asparagine depletion in all patients.[24] However, this dose reduction of PEGasparaginase should be used and guided by careful monitoring of asparaginase activity levels. There is a need in the future to evaluate this dose reduction with respect to outcome and toxicity data. Of interest, a dose reduction of PEGasparaginase could lead to cost savings; this should also be studied.

Second, we found a high incidence of inactivation of PEGasparaginase (22% clinical allergy and 8% silent inactivation) in the intensification phase because of antibody development against native *E coli* asparaginase, which was used in induction. This implies that PEGasparaginase should be used upfront during the induction course instead of native *E coli* asparaginase because this has been shown to result in less antibody formation.[16] A similar inactivation rate of PEGasparaginase (36%) was found 1 week after the PEGasparaginase course by Müller et al using the same asparaginase regimen in induction and a single PEGasparaginase in reinduction.[25] However, they reported no allergies in reinduction. If a subsequent second PEGasparaginase course was administered, we believe that the allergy rate of PEGasparaginase would be increased. An important finding is that even very mild allergic reactions (grade 1) also necessitate a switch to *Erwinia* asparaginase. Continuing with PEGasparaginase combined with pretreatment of clemastine and hydrocortisone is not useful because PEGasparaginase activity levels remain 0 (Figure 1A).

Third, drug monitoring is useful because it detects too high levels in some of the patients and, even more important, silent inactivation in other the patients. Detection of silent inactivation is important to prevent useless continuation of an inactive asparaginase product, which may lead to a worse EFS as shown by Panosyan et al and Vrooman et al.[8,12] Nevertheless, drug monitoring is the only way to detect cases of silent inactivation of asparaginase agents.

Fourth, in the case of allergy to or silent inactivation of PEGasparaginase, patients can be treated effectively with *Erwinia* asparaginase. The majority of the patients that switched to *Erwinia* asparaginase showed effective asparaginase activity levels during the first 2 weeks of *Erwinia* asparaginase, namely median trough activity level of 183 U/L (48-hour level) and 93 U/L (72-hour level) and asparaginase activity level ≥100 U/L in 100% (48-hour level) and 33% (72-hour level) of the patients. Similar rates were found by Vrooman et al: 83% (48-hour level) and 45% (72-hour level) using a dose of 25 000 IU/m^2 3 times per week intravenously.[26] These activity levels were lower compared with that of the study by Salzer et al; they found 645 U/L (48-hour level) and 248 U/L (72-hour level) as median trough activity levels and asparaginase activity levels ≥100 U/L in 93% (48-hour level) and 88% (72-hour level) of the patients using intramuscular *Erwinia* asparaginase in a dose of 25 000 IU/m^2 3 times per week.[27] The route of *Erwinia* asparaginase administration might explain the higher median asparaginase activity levels that were found by Salzer et al.[27] However, previous studies have shown that no differences in mean asparaginase activity levels, asparagine depletion, and AAAs were found after intravenous or intramuscular administration of *Erwinia* asparaginase.[16,28,29]

Only 2/59 (3%) developed an allergy to *Erwinia* asparaginase in our study. Please note that this study does not allow comparison of allergy rates to *E coli* asparaginase (including the pegylated form) and *Erwinia* asparaginase because *E coli* asparaginases were given in induction and intensification with an asparaginase-free interval of 4 months, whereas *Erwinia* asparaginase was administered continuously without such interval.

Fifth, the mean asparagine levels for both preparations were below the detection level of 0.5 μM as used by others.[14,30-32] We observed that asparagine levels were not always completely depleted with our detection level of 0.2 μM[21] in *Erwinia* asparaginase–treated patients in contrast to PEGasparaginase. This may simply reflect the differences in serum drug levels of these 2 compounds. With our very low LLQ of 0.2 μM,[21] 19/57 patients (33%) showed no complete asparagine depletion. If the threshold levels from the literature are used (mean of 0.5 μM), 9 of 57 patients (16%) showed incomplete asparagine depletion.[14,30-32] Samples with *Erwinia* asparaginase activity levels >100 U/L and asparagine >0.2 μM were also found in 9 of 57 patients (16%).

Why this difference in asparagine levels during asparaginase therapy exists between *Erwinia* asparaginase and PEGasparaginase is unclear. Measuring asparaginase activity levels is preferred over

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measuring asparagine levels to monitor the efficacy of asparaginase therapy because, if not properly handled, asparagine is very rapidly degraded ex vivo in the tube by asparaginase leading to false low asparagine levels.[33] It is remarkable that the glutamine levels of *Erwinia* asparaginase–treated patients were lower as compared with those receiving PEGasparaginase irrespective of the much lower serum activity levels of *Erwinia* asparaginase. This can be explained by the higher glutaminase activity of *Erwinia* asparaginase.[34] Although glutamine is broken down to glutamic acid by asparaginase, this does not lead to glutamine depletion because this is supplemented from other organ stocks in vivo.

Sixth, our study shows that the presence of AAAs is related to allergy to and silent inactivation of asparaginase as shown by others,[10,20] but predicting asparaginase allergy or silent inactivation based on antibody formation is hampered by low specificity (64%) of the test. The specificity of the Coli-AAA test in intensification was higher, 73%, but still not perfect. The levels of PEG-AAAs were above the cutoff in almost all allergic patients after the first PEGasparaginase infusion and negative in children without an allergy. The specificity of the PEG-AAA test is 100% to predict an allergy to or silent inactivation of PEGasparaginase in intensification. However, the 2 patients with an allergy at the first PEGasparaginase infusion had no detectable PEG-AAAs (day 0 of intensification). And *Erwinia*-AAAs were found in 38% of the patients but were not associated with inactivation of asparaginase. So, measuring asparaginase levels is a more direct and more accurate way of drug monitoring than measuring AAAs. It has been reported that females and toddlers are more prone to develop allergies.[35] However, we found no relation between age or gender and allergy or antibody formation.

In conclusion, the use of native *E coli* asparaginase in induction leads to a significant rate of allergy to and silent inactivation of PEGasparaginase in intensification. Switching to *Erwinia* asparaginase in case of allergy to or silent inactivation of PEGasparaginase leads to effective asparaginase activity levels in most patients, but close drug monitoring remains necessary to ensure adequate drug levels. The relevance of AAAs in clinical practice appears to be limited. It is more useful to monitor the serum asparaginase activity levels. In the absence of allergy or silent inactivation, PEGasparaginase activity levels are too high with a dose schedule of 2500 IU/m^2 every other week.

This study has therefore resulted in significant changes in the use of asparaginase in the DCOG ALL-11 protocol. PEGasparaginase is used instead of native *E coli* asparaginase upfront in the induction, and the starting dose of PEGasparaginase has been lowered to 1500 IU/m^2. Also, a therapeutic drug–monitoring program is now used to individualize the PEGasparaginase dose and to detect silent inactivation. In case of allergy or silent inactivation, patients are switched to *Erwinia* asparaginase with therapeutic drug monitoring to allow individualized dosing of *Erwinia* asparaginase.

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Authorship

Contribution: W.H.T., R.P., and I.M.v.d.S. designed, analyzed, and interpreted the clinical data; C.L.-K. was responsible for the measurements of asparaginase activities and amino acid levels; M.V.R. was responsible for the *Erwinia*-AAAs; G.J.L.K., D.M.W.M.t.L., M.B.B., C.v.d.B., W.J.W.K., and W.J.E.T. were responsible for the inclusion of patients in the other centers; W.H.T. and W.C.J.H. did the statistical analysis; R.P. and I.M.v.d.S. supervised this research; W.H.T., R.P., and I.M.v.d.S. were responsible for the manuscript preparation; and all authors revised the article critically for important intellectual content and approved the final version to be published.

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A prospective study on drug monitoring of PEGasparaginase and *Erwinia* asparaginase and asparaginase antibodies in pediatric acute lymphoblastic leukemia

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Supplemental file accompanying the paper:

A prospective study on drug monitoring of PEGasparaginase and *Erwinia* asparaginase and asparaginase antibodies in pediatric acute lymphoblastic leukemia

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Supplemental methods

Antibodies against PEGasparaginase (Oncaspar®) and native *E.coli* asparaginase (medac®, Germany)

Briefly, Nunc MaxiSorp^{tm} microplates were coated with native *E.coli* asparaginase or PEGasparaginase (diluted to protein concentrations of 2 or 1 µg/mL in PBS, respectively) over night at 5°C. After one blocking step applying 15% (v/v) foetal calf serum in PBS for 3 hours at 37°C and two washing steps with PBST (PBS/0.05% Tween 20), the plates were preserved with an in-house preservation buffer (a sugar-containing PBS), dried, sealed under vacuum and stored at 5°C. Serum samples were diluted 1:50 and 1:300 (for anti-PEGasparaginase and anti-*E.coli* antibodies detection, respectively) in sample diluent (PBST with new-born calf serum and preservatives). On each microplate a blank (sample diluent), one negative and two positive controls (consisting of human sera) were measured to confirm validity of each test run (see below). A 50 µL/well (duplicate determination) of each sample and control were incubated for 1 hour at 37°C. All wells were washed three times with PBST.

The presence of bound immunoglobulins was detected using horseradish peroxidase-labelled goat anti-human IgG/M F(ab')2 antiserum (Dianova, Hamburg, Germany; final dilution depending on lot reactivity about 1:50,000) and a chromogen/substrate solution containing tetramethylbenzidine/peroxide (TMB, medac, Hamburg, Germany). A 50 µL conjugate per well were incubated for 1 hour at 37°C, followed by three washing steps and a 30-min incubation of 50 µL/well TMB at 37°C. The chromogenic reaction was stopped with 100 µL/well 0.5 M sulphuric acid. Photometric reading of optical densities (OD) was done at 450 nm (reference wavelength 620 nm). In valid test runs OD values of blank had to be <0.05, of negative control <0.1 and of positive controls within appropriately predefined lot-specific

ranges. Cut-off values were defined during assay validation as OD of the negative control plus 0.25 (anti-PEGasparaginase assay) or plus 0.13 (anti-*E.coli* asparaginase assay) by investigation of 128 presumably negative human sera allowing less than 5% samples above cut-off. Sixty-four samples of blood donors from Medical School Hannover (Germany) and 64 samples of newly diagnosed asparaginase naive ALL patients served as negative controls. All samples were assessed twice independently by two persons yielding highly similar results. Within this assumed negative panel 5 samples each (4%) revealed OD values above these cut-offs. To account for regular assay variations a grey zone of cut-off ± 10% was defined. Samples with ODs within this grey zone were evaluated as equivocal, those above as positive, and below as negative.

Antibodies against *Erwinia* asparaginase (Erwinase®)

Serum IgG antibodies against *Erwinia* asparaginase were measured by ELISA. For antibodies to *Erwinia* asparaginase, samples were defined positive if the natural log of its OD reading at a 1:400 dilution of serum was greater than 1.96 standard deviations above the negative control processed mean (using Westgard rules) as previously described.[1]

Statistics

PEGasparaginase and *Erwinia* asparaginase activity levels had to be transformed logarithmically in order to get approximately normal distributions (as shown by the Shapiro-Wilk test). Asparaginase activity levels equal to 0 U/L were replaced by 4 U/L in order to allow the logarithmic transformation. The LLQ of asparaginase activity levels was set at <5 U/L, for further statistical calculations, we used 4 U/L in all asparaginase analysis. Pairwise comparisons of either week PEGasparaginase activity, two-week PEGasparaginase activity and *Erwinia* asparaginase activity levels were made using the paired t-test.

Changes over time of PEGasparaginase and *Erwinia* asparaginase activity levels were evaluated using mixed models analysis of variance (ANOVA), also investigating the relation with age and gender. The mean values for the asparaginase activity levels were estimated by backtransforming the mean of log-values.

We evaluated the sensitivity and specificity with 95% confidence interval of Coli-AAA at the start of the consolidation phase (at day 79) for the development of an allergy to or silent inactivation of PEGasparaginase at the start of the intensification phase (at day 140).

Supplemental results

ANOVA estimates of PEGasparaginase activity levels

Supplemental Figure 2 presents the patients without allergy and without silent inactivation of PEGasparaginase. The mean values of PEGasparaginase activity levels were estimated at 899 U/L, much higher than 100 U/L required for complete asparagine depletion. The week PEGasparaginase activity levels were estimated at 1,679 U/L and were significantly higher as compared to the trough levels ($p<0.001$). Before start of therapy, the PEGasparaginase activity levels were zero. After the first and second PEGasparaginase dose, the mean values changed significantly ($p<0.001$).

The trough levels, thereafter, did not change significantly between week 4 till week 26 as shown by paired t-test and indicating stability after two PEGasparaginase infusions. Only before the last PEGasparaginase was given (week 28), a significant increase of the PEGasparaginase activity level after the previous infusion (week 26) was seen ($p=0.01$). The week PEGasparaginase activity levels at week 3, 9, 15 and 25 did not change significantly.

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Legends to Supplemental Figures

Supplemental Figure 1-A

The Dutch Childhood Oncology Group ALL-10 protocol.

Supplemental Figure 1-B

The intensification/continuation phase of the Dutch Childhood Oncology Group ALL-10 protocol (medium risk group, MRG).

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Supplemental Figure 2

Serum PEGasparaginase activity levels over time (mean ± SEM) in a dose of 2,500 IU/m^2 in children without allergy to and without silent inactivation of PEGasparaginase.

Closed circles show the trough levels; week levels after the previous PEGasparaginase dose are shown by open circles.

Supplemental Figure 3

Relations between serum PEGasparaginase (A) and serum *Erwinia* asparaginase (B) activity levels with serum asparagine levels.

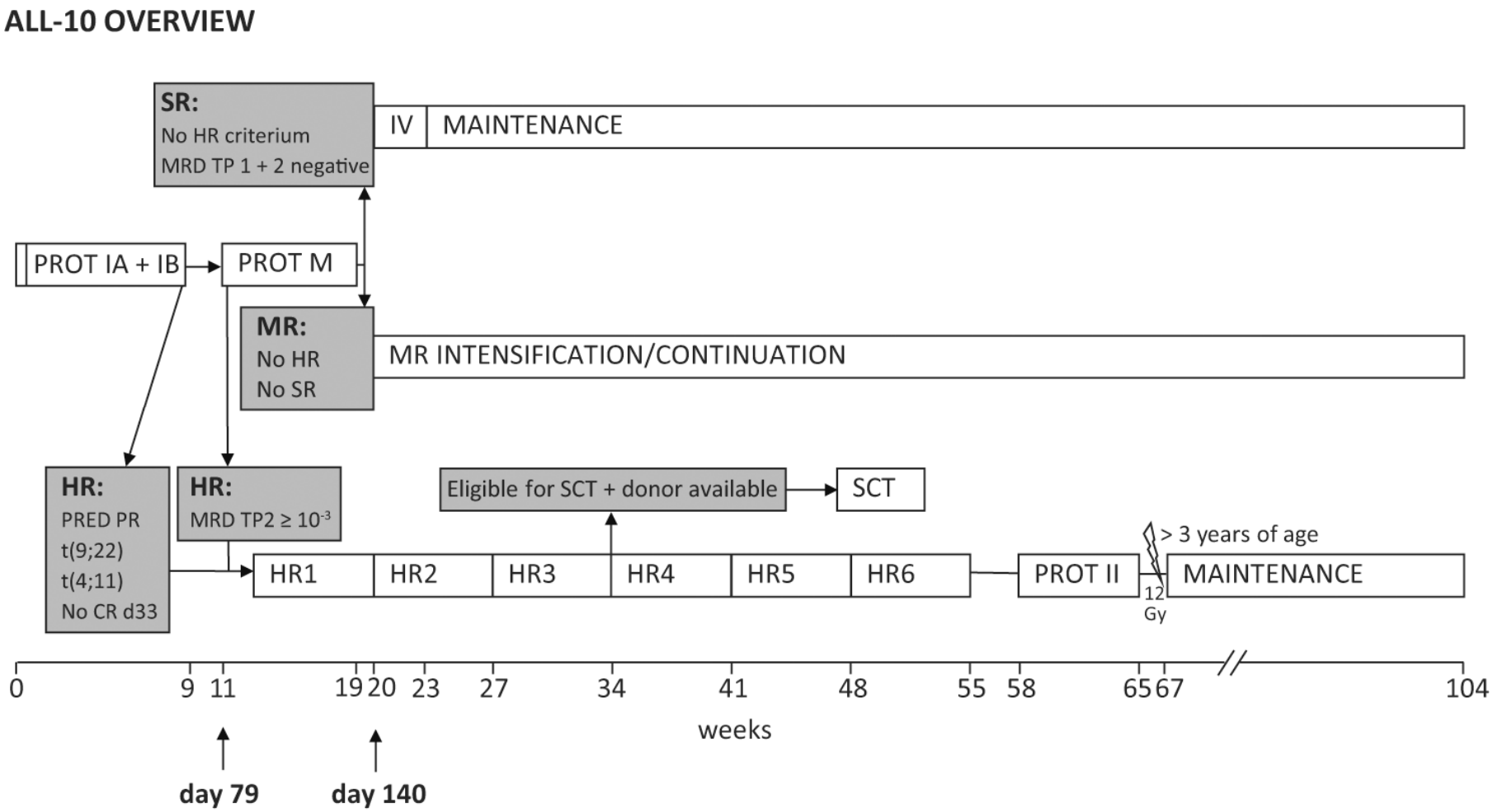
Normal values of asparagine are; 40-80 μM, the asparaginase activity levels were then below LLQ. In Figure 3-B, the horizontal dotted line indicates the *Erwinia* asparaginase activity level of 100 U/L which is associated with complete asparagine depletion. The vertical dotted line indicates the asparagine level of 0.5 μM based on different laboratory reference values in the literature to define (complete) asparagine depletion. Figure 3 A-B displays more than one sample of each study patient.

Supplemental Table 1: Characteristics of patients in the "PEGasparaginase study" and in the "*Erwinia* asparaginase study".

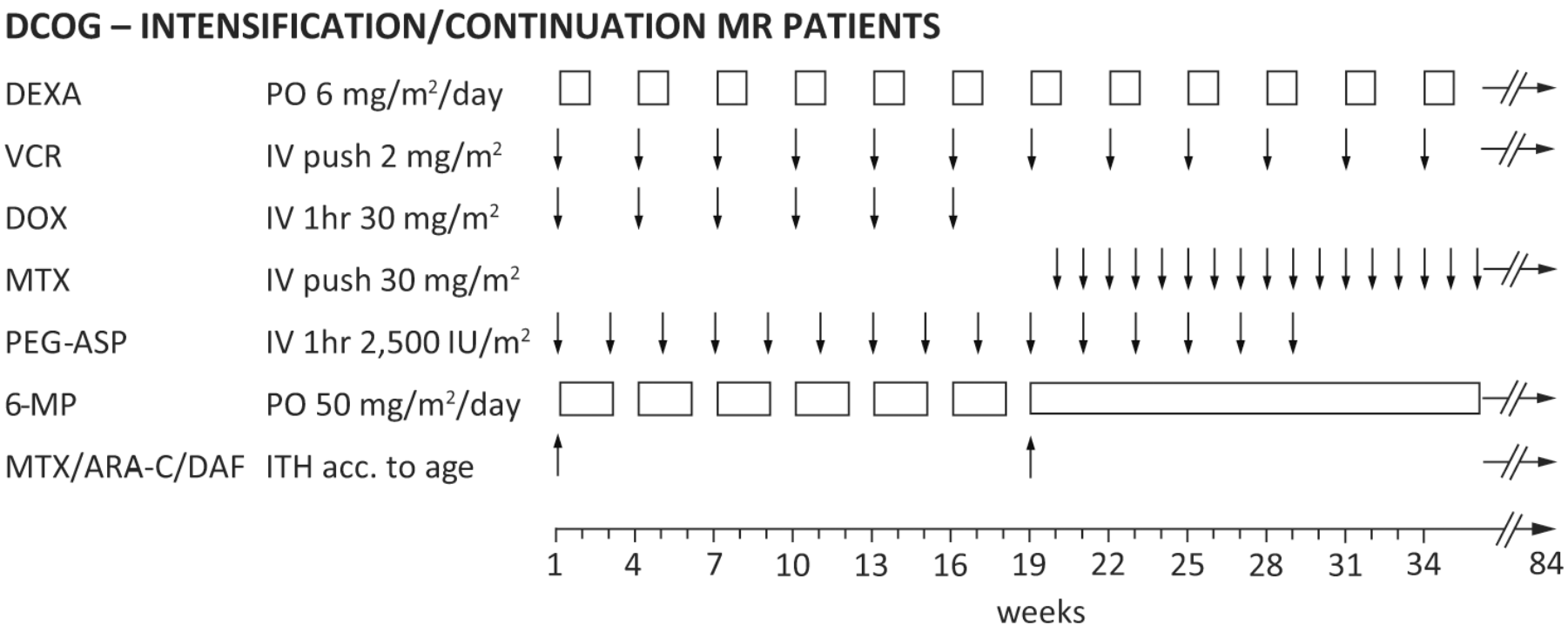
	PEGasparaginase study	Erwinia *asparaginase study*
N	89	59
Gender		
Boys	44 (49%)	36 (61%)
Girls	45 (51%)	23 (39%)
Median age (range) at diagnosis (yr)	4.9 (1.2-16.2)	7.0 (1.8-17.5)
Age category 1-2 yr	4 (4%)	1 (2%)
Age category 2-6 yr	48 (55%)	27 (46%)
Age category 6-12 yr	22 (25%)	14 (24%)
Age category 12-18 yr	15 (17%)	17 (29%)
Immunophenotype		
B-ALL	78 (88%)	53 (90%)
T-ALL	11 (12%)	6 (10%)
No. of participating center	2	7
Allergy (CTCAE criteria)		
Grade 1	6 (7%)	0
Grade 2	7 (8%)	1 (2%)
Grade 3	7 (8%)	1 (2%)
Grade 4	0	0
Occurrence of allergy		
First infusion	2/20 (10%)	0
Second infusion	18/20 (90%)	0
Other	0	2/59 (3%)*
Silent inactivation		
yes	7/89 (8%)	0

* one patient had an allergy to *Erwinia* asparaginase at the fourth infusion and the other patient at the sixth infusion.

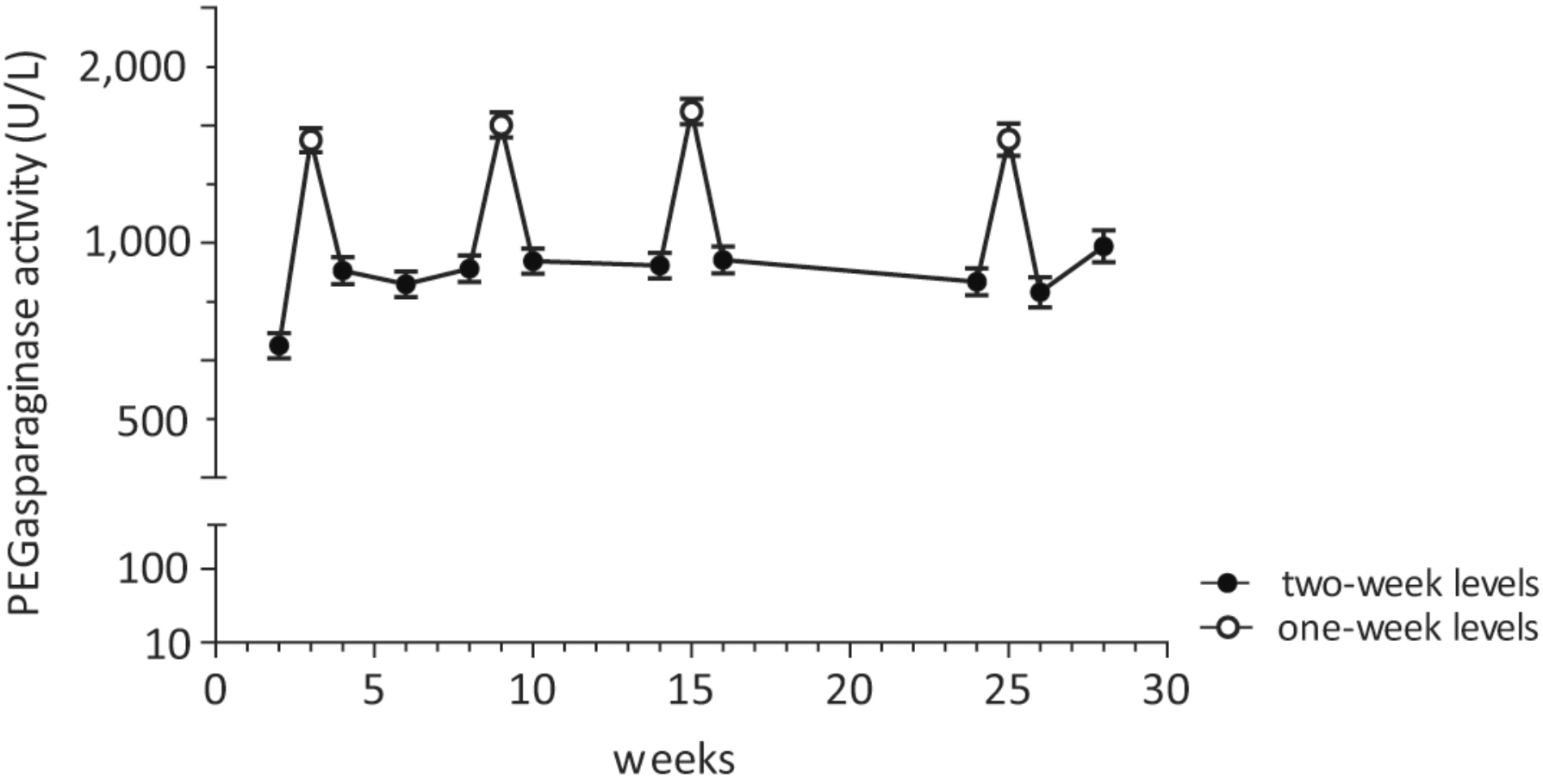
Supplemental Figure 1-A: The Dutch Childhood Oncology Group ALL-10 protocol.



Supplemental Figure 1-B: The intensification/continuation phase of the Dutch Childhood Oncology Group ALL-10 protocol (medium risk group, MRG).



Supplemental Figure 2: Serum PEGasparaginase activity levels over time (mean ± SEM).



Supplemental Figure 3: Relations between serum PEGasparaginase (A) and serum *Erwinia* asparaginase (B) activity levels with serum asparagine levels.

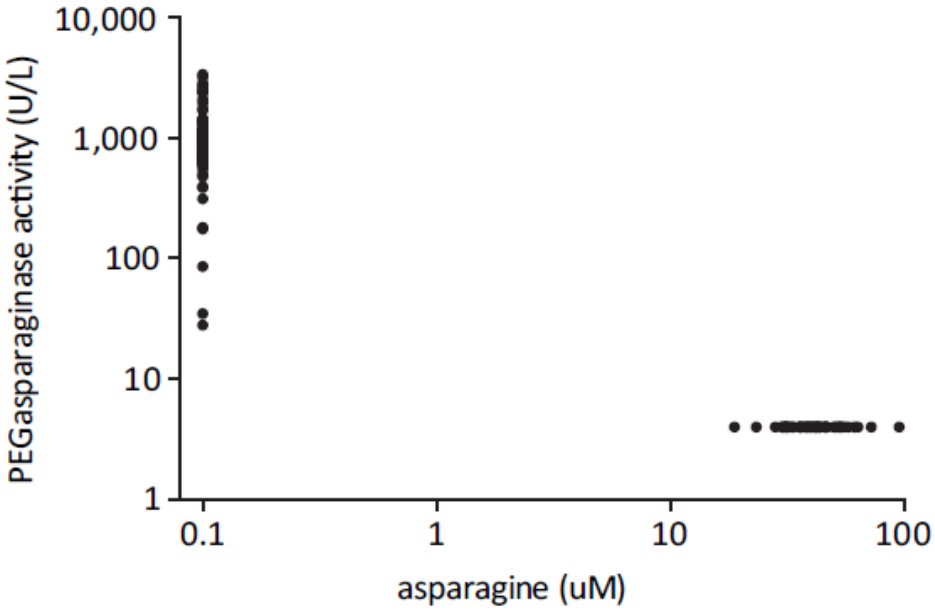


Fig.3-A

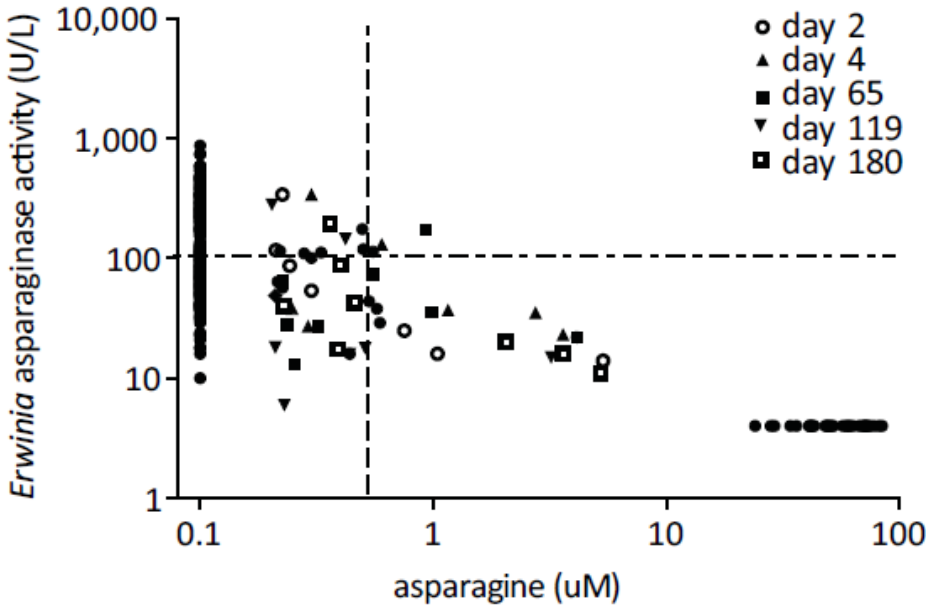


Fig.3-B